

AD A095619

18/11/81
SECURITY CLASSIFICATION OF THIS PAGE (When Data Entered)

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REPORT DOCUMENTATION PAGE

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1. REPORT NUMBER 19 12286.5-GS ✓ AD-A095619		2. JOINT ACCESSION NO. N/A	3. RECIPIENT'S CATALOG NUMBER N/A
4. TITLE (and Subtitle) 6 Investigations of Acoustic-Seismic Effects at Long Range: Early-Arriving Seismic Waves from Apollo 16		5. TYPE OF REPORT & PERIOD COVERED REPRINT	
7. AUTHOR(s) 10 I. Dalins V. H. McCarty G. Kaschak W. L. Donn		8. CONTRACT OR GRANT NUMBER(s) 15 DAAG29-74-G-0172 ✓	
9. PERFORMING ORGANIZATION NAME AND ADDRESS Columbia University Palisades, NY 10964 11 29 Nov 72		10. PROGRAM ELEMENT, PROJECT, TASK AREA & WORK UNIT NUMBERS N/A	
11. CONTROLLING OFFICE NAME AND ADDRESS US Army Research Office PO Box 12211 Research Triangle Park, NC 27709 12 7		12. REPORT DATE Nov 74 24 Nov 76	
14. MONITORING AGENCY NAME & ADDRESS (if different from Controlling Office)		13. NUMBER OF PAGES 6	
		15. SECURITY CLASS. (of this report) Unclassified	
		15a. DECLASSIFICATION/DOWNGRADING SCHEDULE	
16. DISTRIBUTION STATEMENT (of this Report) Submitted for announcement only			
17. DISTRIBUTION STATEMENT (of the abstract entered in Block 20, if different from Report) DTIC ELECTED FEB 27 1981 S B			
18. SUPPLEMENTARY NOTES			
19. KEY WORDS (Continue on reverse side if necessary and identify by block number)			
20. ABSTRACT (Continue on reverse side if necessary and identify by block number)			

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Investigations of acoustic-seismic effects at long range: early-arriving seismic waves from Apollo 16

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(Received 29 November 1972; revised 5 February 1974)

A reasonably comprehensive technical effort is described dealing with the investigations of acoustically generated seismic waves of Apollo 16 and Apollo 17 origin along the eastern seaboard of the United States. This expanded effort is a continuation of earlier, rather successful detections of rocket-generated seismic disturbances on Skidaway Island, Georgia. The more recent effort has yielded few positive results other than a recording of an early-arriving seismic wave from Apollo 16 that was detected in Jacksonville. Evaluation of the negative results obtained in the Fort Monmouth area, with earlier studies of infrasound, local weather conditions, and geology, could be advantageous in the process of trying to gain a better insight into the acoustic-seismic resonance mechanism requiring phase-velocity matching at the atmosphere-ground interface. The evaluation of the recording of early-arriving seismic disturbances in Jacksonville also yielded certain new information about this acoustic-seismic resonance phenomenon.

Subject Classification: 28.20, 28.30, 28.55; 40.50; 50.55.

INTRODUCTION AND SITE SELECTION

During the Apollo 16 launch on 16 April 1972 (12:45 p.m. EST), attempts were made to detect and monitor acoustic-seismic effects at several locations along the eastern seaboard: Kennedy Space Center, Florida; U.S. Naval Air Station, Jacksonville, Florida; Skidaway Island, Georgia (near Savannah); and Ft. Monmouth, New Jersey. Except for omission of Skidaway Island, the same general locations were utilized during the Apollo 17 launch on 7 December 1972 (12:33 p.m. EST), although some local changes were made in locating the instrumentation in a more convenient and otherwise more appropriate area.

In selecting these sites, the authors were guided by the fact that strong seismic signals generated by a resonance mechanism involving phase-velocity matching at the ground-air interface had been observed on Skidaway Island during the Apollo 13 and 14 launches.¹ The technical effort described herein is to be regarded as a follow-up exploration of trying to detect rocket-generated seismic effects and obtain more elaborate details of the acoustic-seismic resonance phenomena.

Instrumentation sites at the Ft. Monmouth location were chosen in order to ascertain infrasound-originated seismic waves at distances much larger than Skidaway Island, i.e., of the order of 1400 km or more. During numerous previous observations, both at Ft. Monmouth as well as at Palisades, New York (Lamont-Doherty Observatory), relatively strong infrasound signals have been reported.²⁻⁴ The associated seismic effects were

expected from what had been learned during previous observations on Skidaway Island. Sandy ground and what appears to be ground areas with unconsolidated sediment seem to be in abundance under Ft. Monmouth jurisdiction to suit these seismic investigations. The necessity for the unconsolidated sediment of some thickness (of the order of half a wavelength, i.e., 50 m or more) to be in the path of infrasound had been observed on Skidaway Island (Apollo 13 and 14), and the consequences of its absence had been detected in Bermuda and on Grand Bahama Island during the Apollo 15 launch of 26 July 1971 (9:34 a.m. EDT) (unpublished data, I. Dalins and V. McCarty, 1971). Rigid coral rock formations intermixed with beach sand and decaying vegetation appears to be inadequate for allowing phase-velocity matching between the infrasound disturbance in air and the Rayleigh waves at the ground surface. In an attempt to achieve the conditions that closely resemble Skidaway Island, three seismographs were located in a triangular pattern in the swampy region of Ft. Monmouth (called New Deal Site). Microseismic background indicated a steady 2-Hz background originated apparently by the waves in the stormy seas a short distance away. This microseismic background limited the ability to operate the seismographs on the desired sensitivity range of 100 mμ/V. On the subsequent launch, attempts were made to avoid this microseismic background by locating the seismographs farther inland on higher and drier ground. In spite of this effort, the interference from the 2-Hz microseismic background persisted.

The Skidaway site was chosen as reference, with one

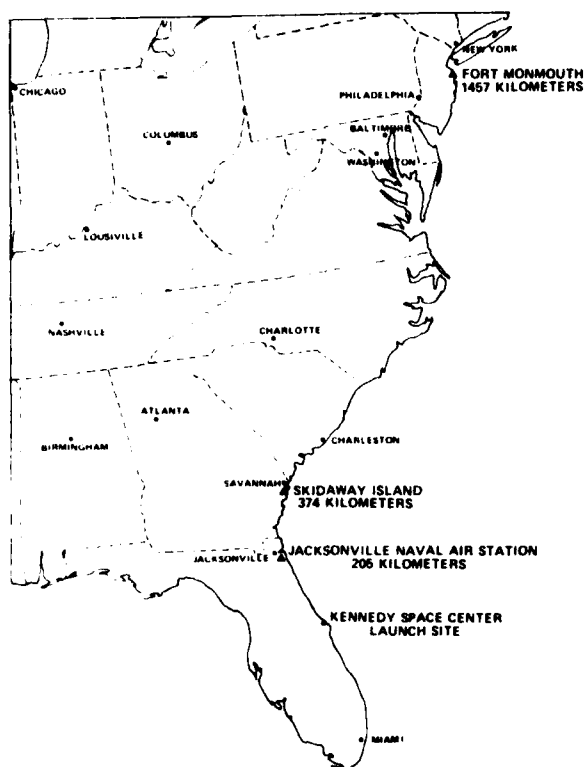


FIG. 1. Map showing location of sites where acoustic-seismic effect studies were made along the U.S. eastern seaboard.

seismograph and two aerophones during the Apollo 16 launch and none during the Apollo 17. The rationale in

this choice was that the recorded signal there would assist in evaluating by comparison the infrasound-generated seismic effects at other instrument locations along the eastern seaboard. Since no readily recognizable seismic or infrasound signal was detected at Ft. Monmouth, this choice of a site on Skidaway was good, and the extra effort was quite justified. Considerably weaker seismic signals and no readily recognizable infrasound signals were recorded when compared to the Apollo 13 and 14 launches. This is attributed to the weakened upper atmosphere sound channel that occurs during summer and the transitional months, which include April.⁴ It has been shown by the authors of this reference that strong infrasound signals are received at Ft. Monmouth and Palisades when stratospheric winds have strong components in the direction of propagation of the infrasonic signal. This condition apparently is also responsible for the weakened signal at Skidaway during the Apollo 16 launch.

During the Apollo 17 launch, infrasonic signal observations at Ft. Monmouth were hampered by the local weather conditions, i.e., a cold front was passing the New York-New Jersey area with locally gusty winds and turbulent air which interfered with atmospheric sensors as well as with seismograph operations at the desired sensitivity levels. It appears that some infrasound signals were received at Palisades but not at Ft. Monmouth, which indicates that the stratospheric winds were also not in the ideal direction.⁴ Some changes of the micro-seism signal pattern were observed when the signal was expected during both launches, but this could not be supported by analysis with analog as well as digital methods.

The Jacksonville Naval Air Station was chosen as a

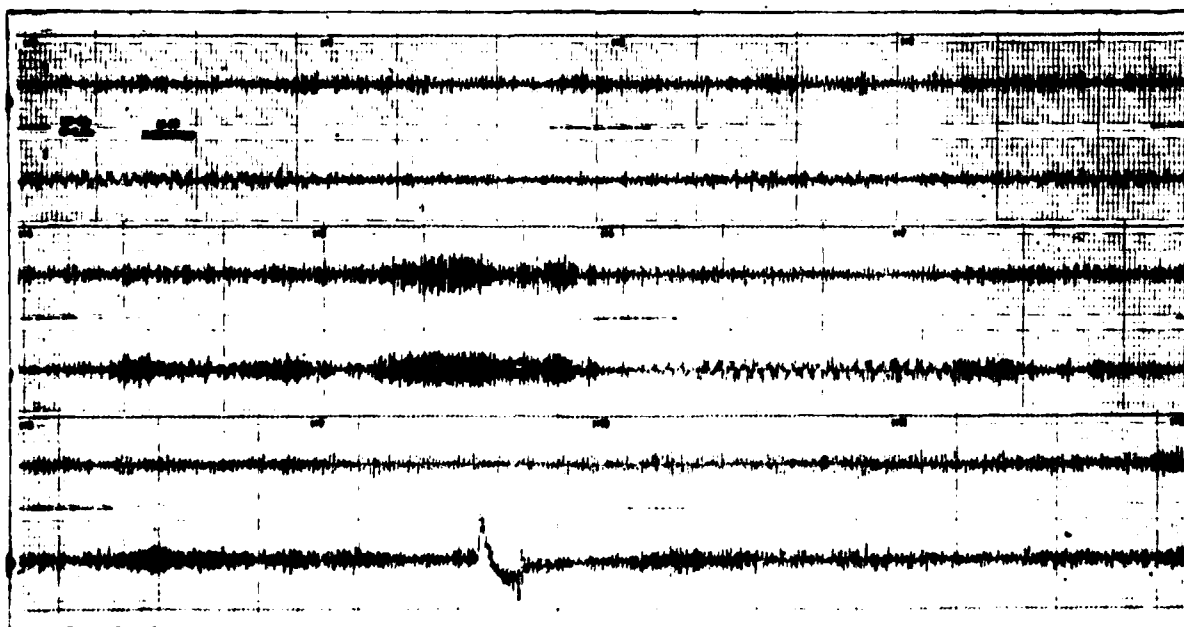


FIG. 2. Apollo 16-originated seismic signal early arrival at $t + 4$ min, 17 sec at U.S. Naval Air Station in Jacksonville, Fla. Amplitude 50 $m\mu$ full scale. Spurious signal at approximately $t + 9$ min, 30 sec of instrumental (servo loop in the seismograph) origin.

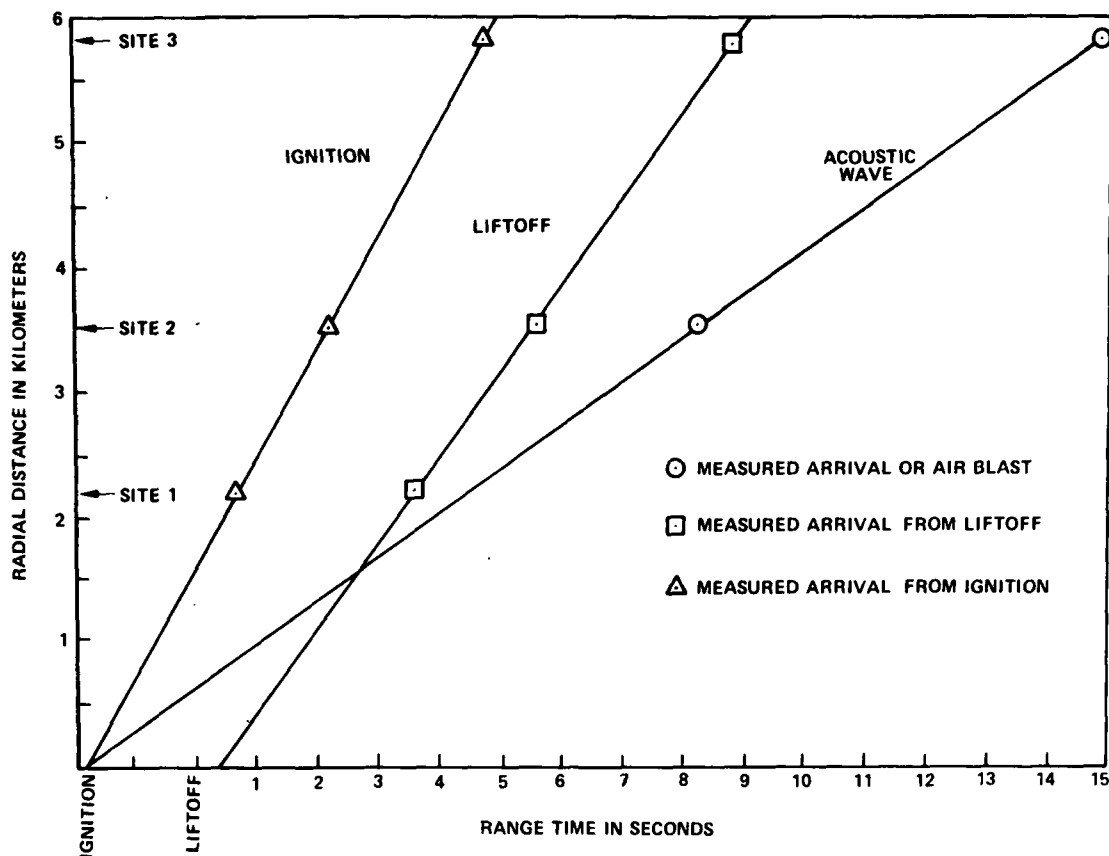


FIG. 3. Plot of "early-arriving" (higher than ambient speed of sound) signals from ignition and liftoff. The estimated seismic wave velocity from ignition 883 m/sec; from liftoff 696 m/sec; ambient atmospheric sound velocity 343 m/sec.

site for the investigations, because it is situated in a zone where no appreciable amount of infrasound signal should reach the ground according to ray-tracing techniques, especially during the summer as well as the transitional months.⁴ Observation of seismic signal arrival with the ambient speed of sound would shed light on certain inaccuracies in the ray-tracing method; i.e., leakage from the upper atmosphere sound channel and/or certain unique and new facets of the acoustic-seismic resonance phenomenon that enhances the seismic signal production in spite of weak or absent atmospheric components. The observations on Skidaway during the Apollo

13 and 14 launches gave strong indications of this possibility.¹ During the Apollo 17 launch, the U.S. Naval Air Station Cecil Field was utilized to locate two seismographs. This installation is more inland, and, therefore, a reduction of the associated microseisms originated by the ocean should diminish. Seismographs and microphones were also located at NASA's Kennedy Space Center during both the Apollo 16 and 17 as well as many earlier launches.⁵ As far as these investigations of long-range acoustic-seismic effects are concerned, this site contributed very little. Three microphones were located at various heights in the 150-m-high weather tower about



FIG. 4. Electronic seismic signal analysis in analog form: cospectra (CO) or in-phase component and quadrature (Q'AD) or 90-deg out-of-phase component between the radial (Y) and vertical (Z) component as shown in Fig. 2.

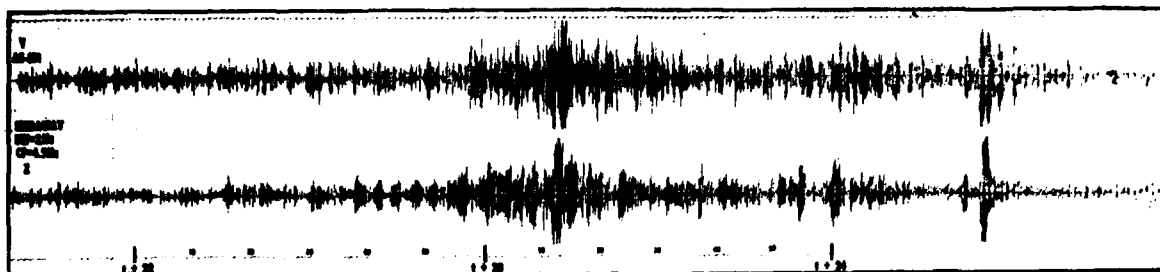


FIG. 5. Apollo 16-originated infrasound-generated seismic signal arrival corresponding to ambient speed of sound on Skidaway Island, GA. The arrival time estimated to be a few seconds after $t + 22$ min. Amplitude $50 \text{ m}\mu$ full scale.

5.5 km from the launch complex, and a seismograph was located near it for gathering data that would yield more insight into the acoustic-seismic resonance mechanism. This is the same mechanism that is essential in the seismic signal generation at long range. Strong, nearly sinusoidal seismic signals with large displacement amplitudes (50μ) have been consistently observed there.⁵

The geographical locations of the instrument sites discussed herein are shown on a map (Fig. 1) together with their respective distances from the launch site.

I. INSTRUMENTATION

The seismographs used at all the sites are essentially the same type as that used on Skidaway Island during the Apollo 13 and 14 launches.¹ They are pendulum types with a capacitance transducer amplifier.⁶ A laboratory-developed pulse duration modulator-multiplexer system is used to permit eight simultaneous recordings of seismic, acoustic, and time signals on a dual-track (stereo) magnetic tape. The pendulum of each seismograph was adjusted to a period of 1 sec, damping 0.75 of critical,

and amplification of about $100 \text{ m}\mu/\text{V}$. This sensitivity had to be reduced to about $250 \text{ m}\mu/\text{V}$ at the Ft. Monmouth location because of the high microseismic level. These seismographs measure displacement of motions with periods shorter than the natural period of the pendulum. Typically, the acoustic-seismic resonance signal is about 4 Hz, i.e., well within the range of the seismograph capability to record as a displacement. Details concerning this instrumentation are available in a NASA report.⁶ Globe capacitor microphones and Fehr and Fisk aerophones were colocated or placed near the seismograph equipment sites. The details about these instruments are discussed elsewhere.⁷

II. EARLY-ARRIVING SEISMIC WAVES AT JACKSONVILLE SITE

Further technical discussion of this paper will primarily be devoted to the only positive results obtained during these investigations. Pertinent data at other locations will be discussed briefly for comparison only. Relatively strong seismic disturbances were observed at the U.S. Naval Air Station in Jacksonville, Florida,

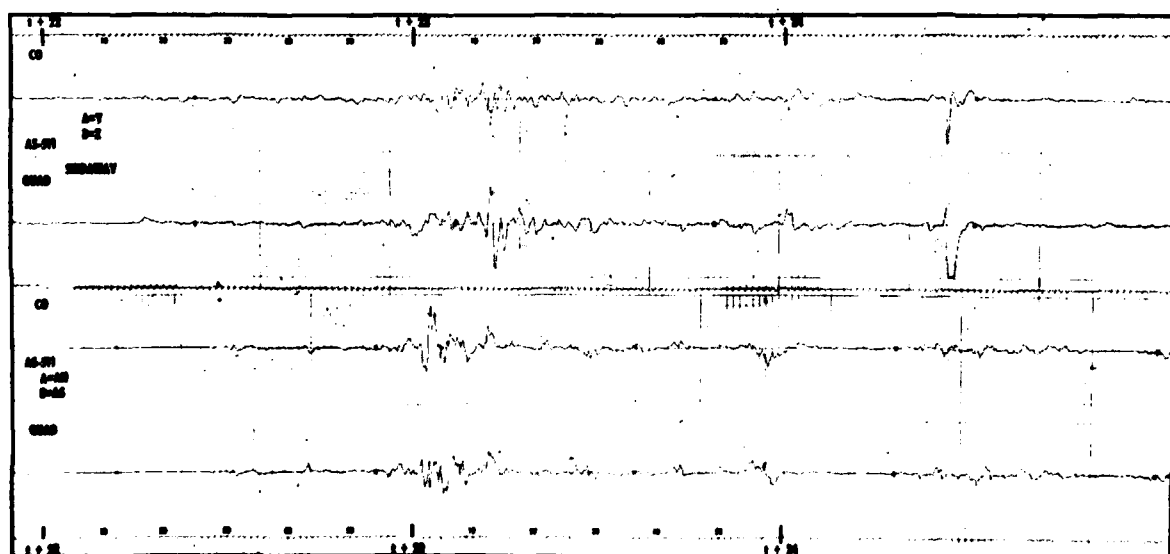


FIG. 6. Electronic analysis of seismic signal (in analog form) as recorded on Skidaway Island. Covariance between radial (Y) and vertical (Z) components appears only $t + 22$ min, 56 sec.

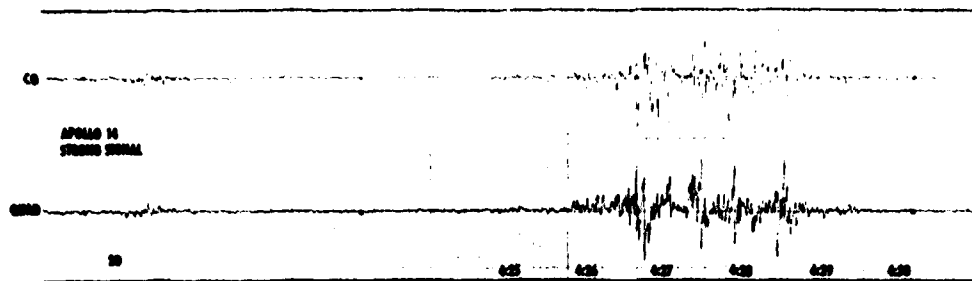


FIG. 7. Electronic analysis of seismic signal as recorded on Skidaway Island during Apollo 14, when strong seismic signal was recorded. Launch 16:03 EST; signal travel time approximately 22 min.

after the Apollo 16 launch. From the arrival time when seismic signal is detected in the radial (Y) as well as in the vertical (Z) components, the average speed of 660 m/sec can be calculated. Unfortunately, only one axis seismograph was used, so that more details about the wave-propagation characteristics (for instance, how the wave moved across a seismograph array) could not be obtained. Both seismic signal components are shown in Fig. 2. No signal could be identified in the transverse axis (X); therefore, it is not shown. Visual inspection of the record indicates that initially a monochromatic signal of 2.5 Hz arrives at the Y component at 4 min, 17 sec after liftoff ($t+4$ min, 17 sec). This value indicates that the propagation speed of the wave is about 797 m/sec. Seismic disturbances which appear to be shear waves with velocities of this magnitude were measured during the second unmanned Saturn V launch (sometimes referred to as Apollo 6) early in 1968. This data is shown in Fig. 3. It was obtained by using three seismographs near the Vehicle Assembly Building (VAB) at the Kennedy Space Center with associated microphones at two of these sites. Extrapolation of these plots to the origin indicates that the wave groups were generated by ignition and liftoff, with slightly different velocities, respectively.

Further evaluation of the seismic signal at the U.S. Naval Air Station in Jacksonville shows that the first bursts of nearly monochromatic 2.5-Hz seismic signals last for about 14 sec; they are followed by second bursts of about equal duration. Subsequently, a stronger monochromatic signal with approximately the same frequency as the initial bursts is seen in both the Y and Z components at $t+5$ min, 12 sec. This seismic signal lasts for about 48 sec. Other weak signal bursts may very well be arriving, but they are too weak to be noncontroversial. The signal as shown in Fig. 2 has been filtered with an LC filter, center frequency (CF) 2.5 Hz and bandwidth (BW) 2 Hz. Analysis of the signal in the analog form has been made with a system manufactured by Spectral Dynamic Corporation of San Diego, California, consisting of SD 109A CO/Quad Analyzer, SD 101A Spectrum Analyzer, SD 101S Slave of above, and SD 104A-5 Sweep Oscillator. The cospectra (CO) or inphase signal component and quadrature (Quad) or 90-deg out-of-phase component of the Z and Y seismic signal of Fig. 2 is shown in Fig. 4. This data analysis clearly shows marked

changes in signal character at $t+5$ min, 12 sec in comparison with the general background. The duration of this strong signal is also clearly identified. The strong signal in the 90-deg out-of-phase component (Quad) implies that the ground motion is nearly elliptical, which is the characteristic feature of Rayleigh waves. Some changes in the background character are noticeable earlier, i.e., $t+4$ min, 17 sec with no noticeable change in the amplitude in CO or Quad. This is in agreement with visual observations that the initial seismic signal arrival occurs only in the radial component.

At this same site, two Globe capacitor microphones were placed north and south of the seismograph site about 150-m apart, and two Fehr and Fisk aerophones were placed east and west about equal distance apart for the detection of infrasound that might arrive there. The data from these sensors were analyzed visually as well as with the Spectral Dynamics System. No distinct signal could be found that would indicate the arrival of Apollo 16-generated infrasound waves. No seismic signal could be detected that would correspond to the arrival with ambient speed of sound. The seismic signal as recorded at the U.S. Naval Air Station in Jacksonville, therefore, cannot be interpreted as originating locally. It is interesting that long-period seismic waves with periods from 10 to 20 sec originated by atmospheric shock waves of Apollo rocket origin have been repeatedly detected in Bermuda.⁶ In qualitative terms, this would indicate that the energy transfer is of the correct order for some wave forms to be detectable in Jacksonville. Confirmation of these observations was sought during the subsequent Apollo 17 launch by placing two seismographs at the U.S. Naval Air Station Cecil Field. Unfortunately, the results were negative.

Somewhat weakened seismic signals from atmospheric coupling of infrasound were received at Skidaway Island after the Apollo 16 launch (no instrumentation was placed there during the Apollo 17 launch). The received signal after filtering is shown in Fig. 5. From the arrival time (22 min, 13 sec) the speed is computed as equivalent to the ambient atmospheric speed of sound. Except for the CO and Quad analysis with the Spectral Dynamics System, no further analyses of the data have been made. The processed analog is displayed in Fig. 6. Similarly analyzed data from the Apollo 14 launch is displayed for comparison in Fig. 7. The original signal

has been discussed in detail elsewhere.¹ The general increase in signal against the background is clearly demonstrated by these displays of data. No recognizable infrasound signal was detected with the two Fehr and Fisk aerophones.

A search was made for early-arriving seismic signals at Skidaway Island. This effort did not yield fruitful results. Observations of weaker signals at Skidaway tend to explain the absence of infrasonic signals in the Ft. Monmouth area because of unfavorable conditions in the stratospheric sound channel.

III. SUMMARY AND CONCLUSIONS

The technical effort described herein does not support the authors' earlier contentions that the acoustic-seismic resonance can be effectively utilized in the study of atmospheric infrasound signals in the presence of locally strong wind noise in the Ft. Monmouth area.¹ It appears that, with the unfavorable wind interference, there may very well be a corresponding interference from stormy seas. The geological structure requirements for the acoustic-seismic resonance to effectively filter out wind noise appear to be more stringent than initially anticipated. More detailed comparison studies of the geological conditions between Skidaway Island and the Ft. Monmouth area are in order before selecting a suitable site for

seismographs.

A seismic signal was detected at the U.S. Naval Air Station at Jacksonville which appeared to be originated by the Apollo 16 launch but which arrived much ahead of the atmospheric disturbance and with a frequency of about 2.5 Hz. The origin of this signal remains unverified, but it is conceivable that this corresponds to shear and Rayleigh waves of the acoustically excited ground area near the Kennedy Space Center where large amounts of acoustic energy are transferred to ground vibrations through the acoustic-seismic resonance mechanism.

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